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Predictive Models for Target Response During Penetration

LDRD-ER 12-ER-064 Final Report

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Introduction

This LDRD ER focused on the development of a new capability for modeling the response of frictional materials to extreme dynamic loading environments such as those encountered during the interaction of an earth penetrator with a geologic target or the interaction of a bullet or a shaped charge with ceramic armor. The effort was motivated by the significant, long-standing and persistent national security challenge posed by Hard and Deeply Buried Targets (HDBT). HDBTs are often used by potential adversaries for the protection of strategic assets. The intelligence community currently estimates that there are more than 10,000 HDBTs worldwide. Not only are HDBTs increasing in number, but also in hardness, making many of these targets, which were already difficult to defeat, essentially invulnerable to existing conventional weapons. This problem is further exacerbated by the projected trends in penetrating weapon capabilities. Compared to existing weapons, future penetrators are expected to weigh less and be smaller in size. Thus, higher impact velocities will be required to maintain similar penetration capability. The combination of higher impact velocity and increased target hardness, impose significant requirements on the design of survivable penetrators capable of holding HDBTs at risk. Because the design margins of existing weapons are relatively small, significant advances in the state of the art will be required to enable a successful transition from the relatively large penetrating weapons in today's arsenals to the smaller, lighter, and faster weapons of the future.

Over the past decade, LLNL has successfully demonstrated a new accelerated approach to the development of advanced conventional munition relying less on empirical testing, and more on modeling and simulation. This approach has significantly truncated the development cycle, resulting in significant savings of both time and budget. Successful application of this approach to the development of earth penetrators is hindered by the fact that the modeling capabilities needed to assess penetrator performance are not mature. Currently used models are empirical; they require extensive calibration against experimental data, and they lack the predictive capability to extrapolate outside the domain for which they are calibrated. The objective of the proposed LDRD ER is to develop three-dimensional modeling capabilities to enable a transition from the current empirically-based approach for assessing penetrator performance, where accuracy hinges on the availability of calibration data, to a physics-based predictive approach, where weapon performance is correlated to complex, non-linear physical processes that occur during weapon-target interaction.

Project Accomplishment

This section provides a short summary of the main project accomplishments. Detailed accounts of the technical approach, new developments and major findings of our research are provided in Aarons *et al.* (2015), Vorobiev *et al.* (2015) and Herbold *et al.* (2015). Aarons *et al.* (2015) was recently submitted to

Computational Geosciences; Vorobiev *et al.* (2015) is in preparation and will soon be submitted to the *International Journal of Impact Engineering*; and Herbold *et al.* (2015) is in preparation and will soon be submitted to *Computer Methods in Applied Mechanics and Engineering*. In addition, results of the research findings have been disseminated to the scientific community through several presentations at scientific conferences and symposia, including the four invited presentations listed below in the Invited Presentations Section.

- Developed a meshing algorithm to create concrete representative volume elements (RVE) model with two constituents (aggregate particle surrounded by mortar material). The method consists of two main steps: 1) packing of aggregate particles which correspond to certain particle size distribution within a volume, 2) meshing both the particle and mortar and setting up cohesive elements between the particles and mortar elements. The development of this capability was a key enabler of the physics-based mesoscale simulations of concrete performed to support the model development effort.
- Developed a novel dynamic fragmentation algorithm and implemented it in a parallel 3D Lagrangian hydrocode (GEODYN-L). The algorithm allows for element decoupling from the mesh into computational blocks, refinement of these blocks into multiple elements, and insertion of cohesive elements between the decoupled blocks and the surrounding elements. Parameters for the cohesive elements (cohesion and friction) are initialized based on the damage tensor history variable accumulated prior the decoupling step. This feature describes the directional nature of the failure process and minimizes numerical biases and mesh dependence. The algorithm was demonstrated to work across CPU boundaries and implemented both in 2D (quad mesh) and in 3D (TET and HEX meshes). A paper describing this unique algorithm is in preparation [Herbold *et al.* (2015)].
- Developed a fragment counting algorithm for use in post-processing mesoscale simulations to quantify damage evolution during loading and to characterize the post failure state of the material. The algorithm has been shown to work across CPU boundaries and has been demonstrated to scale efficiently thus demonstrating utility in the large parallel runs needed for mesoscale studies. A paper describing this algorithm has been submitted to a peer-reviewed journal [Aarons *et al.* (2015)].
- Mesoscale simulations of uniaxial and biaxial experiments have been performed using statistically equivalent representative volume elements constructed using the meshing algorithm described above. Challenging numerical problems encountered during these studies led to further improvements of the method and in particular for Simple Common Plane contacts. Instabilities discovered at the cohesive contacts have been resolved by more accurate representation of the contact area and associated contact forces. In the original version of the common plane the force was applied at the middle of the area which caused some “rocking instabilities” and premature failure at the contacts. Multiple integration points were added at the common plane to alleviate this problem. This algorithm is original, unique and represents a significant advance in the current state of the art of numerical modeling of contact mechanics. Several alternative methods are available, but they are not robust and not relevant for large

deformation problems such as the penetration problem of interest in this study. This sophisticated method is described in detail in Herbold *et al.* (2015).

- Further developments done under the current LDRD allowed us to perform simulations of perforation and penetration into concrete targets using the Lagrangian code GEODYN-L by converting elements experiencing large deformations into DEM particles around the penetrator. Simulations of large scale penetration experiments into concrete targets showed reasonable agreement with data. The deformation histories in these simulations were recorded at locations of interest along the path of the penetrator and used to drive detailed mesoscale simulations, the results of which were then utilized in the development of a physically-based constitutive model for concrete during penetration. This work is described in details in Vorobiev *et al.* (2015).
- A new constitutive model for concrete was developed and implemented. This model includes porous compaction and dilation, pressure-dependent yield, as well as elastic moduli degradation with damage. The damage is based on the amount of bulking porosity generated during deformation. The current model is isotropic and enables transition to an anisotropic model by using a tensor damage variable. Even though it was not planned as a deliverable of the current LDRD, the framework for an anisotropic model has been added, but the transition from the initial isotropic model to the final anisotropic model is only partially completed. The model is implemented as a stand along module and validated in the GEODYN-L code. A working version of this model has also been implemented in the GEODYN material library, which is accessible by multiple LLNL codes including GEODYN, ALE3D, GEOS, and SPHERAL.

Peer-Reviewed Publications

1. L.Ararons,E. Herbold,O.Vorobiev,T.Antoun “A novel algorithm for identifying and labeling connected components in massively parallel simulations,” submitted to *Computational Geosciences*
2. O. Vorobiev,E.Herbold, S.Ezzedine,T.Antoun “A continuum model for concrete informed by mesoscale studies,” in preparation for submission to the *International Journal of Impact Engineering*.
3. E.B. Herbold, S. Johnson, R. Settgast, O.Y. Vorobiev, “Improved Simple Common Plane Contact for Large-Scale Finite Element Methods,” in preparation for submission to *Computer Methods in Applied Mechanics and Engineering*.

Invited Talks

1. T. Antoun, “A multiscale modeling approach for deformation and failure of geologic materials in extreme loading environments,” Center for Computational Earth & Environmental Science Seminar, Stanford University, 11 Nov (2013).
2. T. Antoun, E. Herbold, L. Aarons, O. Vorobiev, “Application of Mesoscale Simulations Toward the Development of Predictive Models for Deformation and Failure of Frictional Brittle Materials,” Keynote presentation at the 22nd International Workshop on Computational Mechanics of Materials (IWCMXXII), Baltimore MD, September 24-26 (2012).

3. T. Antoun, O. Vorobiev, E. Herbold, I. Lomov, "Mesoscale Modeling of the Dynamic Response of Armor Ceramics," Invited presentation, 36th International Conference and Exposition on Advanced Ceramics and Composites, Daytona Beach Florida, USA, January 22-27 (2012).
4. T. Antoun, O. Vorobiev, E. Herbold, S. Johnson "Correlation of Observed Macroscopic Response to Underlying Deformation Mechanisms," Invited presentation, TomoDamage 2012—From post-mortem to dynamic in-situ computed tomography (CT) analysis, Freiburg, Germany, August 29-31 (2012).